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DYNAMIC ANALYSIS OF LARGE SOIL STRUCTURE SYSTEMS(U)
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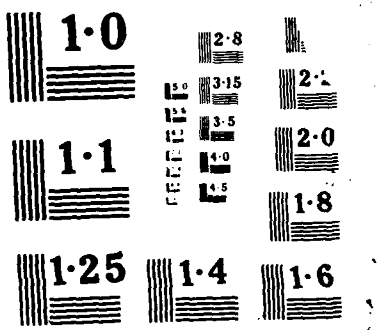
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An EVALUATION of NUMERICAL ALGORITHMS for the NONLINEAR DYNAMIC ANALYSIS of LARGE SOIL STRUCTURE SYSTEMS

ABSTRACT The numerical algorithms developed under the 6.1 Structural Modeling Program are reviewed and evaluated to assess their applicability towards the 6.2 Nonlinear Structural Analysis Program.

An exposition of the currently available numerical methods for the solution of *soil-structure* interaction problems is also performed. Within this framework the work done under the 6.1 Program is evaluated.

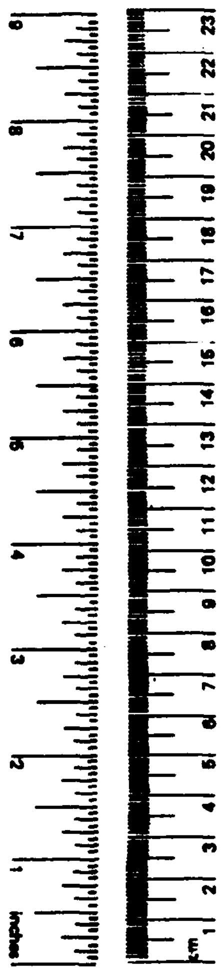
NAVAL CIVIL ENGINEERING LABORATORY PORT HUENEME CALIFORNIA 93043

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

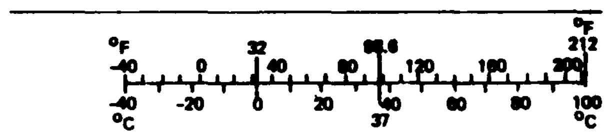
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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numerical algorithms, nonlinear, dynamic, analysis, soil-structure, interaction contact, bounding surface plasticity, boundary element, finite element, reduced coordinates

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The numerical algorithms developed under the 6.1 Structural Modeling Program are reviewed and evaluated to assess their applicability towards the 6.2 Nonlinear Structural Analysis Program.

An exposition of the currently available numerical methods for the solution of soil-structure interaction problems is also

performed. Within this framework the work done under the 6.1 Program is evaluated.

Table of Contents

1. Introduction

The 6.1 Structural Modeling Program at the Naval Civil Engineering Laboratory at Port Hueneme has as a main objective to develop analysis algorithms for the nonlinear analysis of drydocks and other large geotechnical-structural systems. The 6.2 Nonlinear Structural Analysis Program is aimed at implementing those algorithms into a special purpose finite element analysis program that will allow a 3 dimensional nonlinear dynamic analysis of the large structural systems under earthquake and blast type of excitations. This report contains a review and evaluation of these algorithms to assess their applicability towards the 6.2 Program.

The reviewed work is contained in References [1-8]. The issues covered include: reduced modal methods for nonlinear dynamic problems, contact and friction finite element techniques, combination of finite element and recursive boundary element methods, validation of bounding surface plasticity models for saturated cohesive soils and, finally, linear fracture mechanics for concrete.

~~The present~~ work is initiated with an exposition of the currently available numerical methods for the solution of the soil-structure interaction problems in the time and frequency domains. Directions are given as to which of the available methods seem to be more applicable for the problem at hand. In particular, complete and substructure methods in the time domain are presented as the most convenient ones. In view of these algorithms the work done under the 6.1 Program is reviewed and evaluated.

2. Numerical methods for soil-structure interaction problems

Although not a part of the 6.1 Program it is important to explain and evaluate the numerical environment in which the soil-structure interaction problem involved in the analysis of drydocks under earthquake excitation and blast effects, is to be analyzed. A number of different methods, implemented in currently available computer codes, have been used so far for the analysis of such problems. All these methods can be classified in two major groups: frequency domain and time domain methods.

The first group encompasses the majority of available methods and computer codes. The available techniques within the frequency domain are summarized in Fig.1. These can be classified into three major groups: complete, substructure and hybrid methods. Four different problems need be solved for a complete analysis: the site response problem or free field analysis, the scattering of waves due to the presence of the foundation, the impedance problem that yields the complex stiffness terms and the final structural analysis. The flexible volume methods seem to be the more attractive of all of these because they eliminate the scattering problem and also because they take full advantage of the substructure method. Details of the equations involved in each technique are given in [9,10]. The common denominator in all these methods is the basic assumption of linearity in the total response of the system.

The reasons for the popularity of the frequency domain approaches are, firstly, the possibility of dividing the problem into substructures that can be analyzed independently, and secondly, the availability of accurate frequency dependent radiation boundaries that help to considerably reduce the size of the finite element models. However, as pointed out in [9], these two advantages can not hinder the tremendous limitations that arise from the fact that frequency domain techniques can not solve nonlinear (geometric or material) problems. Quasi nonlinear approaches [11,12] have been developed that require a continuous transfer of information between the frequency and time domains. These quasi nonlinear methods lack rigor and demand an exceedingly large computational effort. Another important limitation comes from the fact that frequency domain techniques become numerically inefficient for transient analysis of three dimensional problems. In view of these facts, frequency domain methods do not seem the most appropriate for the kind of problems involved in the transient dynamic analysis of drydocks that involve nonlinear material and contact problems.

A classification analogous to that done with the frequency domain can be done with the time domain methods. Fig. 2 illustrates the available methods in the time domain. Three major groups are distinguished: the complete, the boundary and the volume methods. There is no such a thing as an impedance problem, however the structural analysis now involves the total ensemble soil-structure. In this regard it is important to note that the substructure concept used in the frequency domain is not similar to that currently used in the time domain. The splitting of the model, as done in the frequency domain, is substituted in the time domain by a reduction in the number

of degrees of freedom in parts of the system (substructures) that are subsequently assembled and solved simultaneously. An important observation is that the mechanisms available in the time domain to account for the radiation of energy through the boundaries of the mesh are not as accurate as those available in the frequency domain. This limitation is compensated by having recourse to larger finite element models, and approximate frequency independent dashpots. Nevertheless, satisfactory solutions to the radiation problem in the time domain have been obtained as reported in References [9,13,14].

The volume methods are not applicable to the drydock problem since it involves a superposition scheme at the foundation level which obviously precludes any nonlinear analysis. The two other possibilities are the complete method and the boundary method. The first one allows a full nonlinear analysis of all the ensemble soil-structure problem, however it requires an extensive modeling of the soil profile until a sufficiently rigid bedrock, at which the input motion is to be specified, is encountered. This suffers from the major drawback that unless the bedrock is close to the surface the 3-dimensional model needed for the analysis may become extremely large, thus making the computational cost of analysis prohibitive.

In the boundary method the input motion can be specified at a surface marked by the separation between the linear and nonlinear soil characteristics, as shown in Fig. 3. Its major advantages lie in the following facts:

- The soil below the input boundary can be considered linear and therefore that part of the finite element model may be substructured, thus reducing the size of the final model. This same substructure can be used to solve the scattering problem avoiding part of the extra computational effort involved in this phase of the problem.
- The soil profile can be cut at a closer distance to the structure than that of the complete methods. This distance will exclusively depend on the accuracy required from the energy radiation mechanism at the boundaries of the finite element model.

On the other hand the boundary method has the disadvantage, as compared to the complete method, of having to solve the scattering problem. The input motion, although of a multiple excitation type, is applied in a smaller amount of nodes than in the case of the complete methods.

The factors mentioned above should be weighted with the typical properties of the drydock environment and soil characteristics to decide which of the two proposed methods should be selected for the special purpose analysis program under consideration.

There is no doubt that a 3-D analysis of the types of drydocks under consideration will involve a much greater computational effort than a 2-D analysis. However, it is important to point out that the former becomes necessary, first, when the loading has strong components in the normal direction and, second, when the structural system contains parts, sometimes of vital importance, which do not have plane symmetry and therefore need be analyzed under 3 dimensional assumptions. In particular, for the drydock problem, the analysis of the pump house and the caisson require full 3-D consideration.

With these ideas in mind we can now review the work done under the 6.1 Program and see how they fit into the general formulation of the problem.

3. Reviewed Methods

In the present study several methods developed under the 6.1 Structural Modeling Program have been reviewed to determine their applicability towards the objectives of the 6.2 Nonlinear Structural Analysis Program aimed at drydock analysis. The methods considered include:

a) Reduced coordinates for the solution of large time dependent problems.
b) Contact problems.
c) Combined boundary element and finite element method for the silent boundary effect.
d) Bounding surface plasticity model for soils, and linear elastic fracture mechanics for concrete.

3.1 REDUCED COORDINATES FOR LARGE TIME DEPENDENT PROBLEMS

The work reviewed in this section is reported in References [1,2]. This work is mainly devoted to the construction of algorithms that will reduce the size of finite

element equations and will retain the fundamental properties of the larger original system.

The proposed method can be basically summarized as follows:

1. Use of a series of "Lanczos vectors" (generated taking into account the spatial distribution of the loading) or "Lanczos eigenvectors" to reduce the total size of the finite element equations. The vectors are originated in an inverse setting so that the projection basis is related to the smallest eigenpairs of the system. If resonance is expected, shifting may be used to generate vectors in a given interval of the frequency spectrum.

2. Use a Newmark-Newton time marching scheme for the integration of the reduced set of equations. Each step will require the transformation of the nonlinear stiffness matrices from the finite element coordinates to the Lanczos coordinates, operations that can be performed at the element level, and the solution of the reduced system of equations. Two schemes are proposed to assure convergence. The first one is a time sub-stepping with an integer number of substeps. The second is a recalculation of the vector basis, which will be necessary if the finite element mesh undergoes large deformations. The updating of the basis constitutes one of the most computationally expensive parts of the procedure and this cost may be critical for the overall efficiency of the method. If neither of these two schemes allows convergence, the algorithm will have to be stopped. Alternatives to this problem are currently being searched for by the authors.

The method has been tested in several linear and nonlinear problems yielding very good results.

The proposed method should be very applicable to the nonlinear analysis of the drydock. No testing of the algorithm in large scale problems have been reported, however all the indicated operation counts point to the fact that this reduction method should overcome the direct methods in computational efficiency. This algorithm will also allow the analysis of the large drydock finite element model in a non-supercomputer environment. Several considerations may be suggested:

a) The use of substructures for the analysis at hand is almost imperative. Major advantages in the use of substructures may be found when the same structural

element is repeated several times, and in the possibility of analysis of different components by different teams. In addition, as explained by Clough and Wilson in [15], linear substructures do not need to be updated during the nonlinear iteration process. The use of substructures and mode superposition in nonlinear systems can also be done as shown by Bathe and Gracewski in [16]. Each of the main physical components of the problem: caisson, pumphouse, drydock walls, near field soil and far field soil, can be substructured individually using classical techniques [17-19]. The number of boundary (master) degrees of freedom can be very large (particularly in the walls of the drydock and in the soil system), in this case a multilevel substructuring technique (define substructures of substructures) may be used as explained by Wilson and Bayo in [20]. Proceeding in this fashion will minimize the use of back-up storage, and will allow for the solution of the final set of equations directly in high-speed storage.

A transformation of the component synthesis type can be applied at each substructure level:

$$\begin{bmatrix} u_i \\ u_b \end{bmatrix} = \begin{bmatrix} f_i & T_i \\ 0 & I \end{bmatrix} \begin{bmatrix} Y_i \\ u_b \end{bmatrix} \qquad (1)$$

where u_i and u_b represent the internal and boundary degrees of freedom respectively. f_i and Y_i are the Lanczos vectors and generalized coordinates, respectively. I is the identity matrix and T_i is the static condensation transformation: $-[K_{ii}]^{-1}[K_{ib}]$ which can be obtained by backsubstitution of $[K_{ii}][T_i] = -[K_{ib}]$. The triangularization of K_{ii} can also be used for the calculation of the Lanczos vectors. The proposed algorithm for the generation of reduced Lanczos coordinates can then be used at each substructure level and in the global system to reduce their size, and to capture the inertia effects of the internal degrees of freedom. This substructuring part will require serious thought at the time of computer implementation.

b) As reported in [20,21] the use of the "Lanczos vectors", which are generated taking into consideration the spatial distribution of the loading, gives better (or at least as good) results for earthquake excitation than do the "Lanczos eigenvectors". Furthermore the former are generated at a fraction of the cost

involved in obtaining the structural eigenvectors. It is therefore recommended that the "Lanczos vectors" be used instead of the "Lanczos eigenvectors".

c) A general 3-D earthquake excitation with six different components can be expressed as a product of spatial load vectors and time functions, as follows:

$$F(s,t) = \sum_{i=1}^{6} f_i(s)\, g_i(t) \tag{2}$$

where $f_i(s)$ represents the i^{th} component of the spatial distribution of the loading and $g_i(t)$ the i^{th} time variation function. The Krylov subspace can be generated in this case by using a recurrence sequence that uses "blocks" of vectors corresponding initially to the multiload patterns. It is suggested that this type of generation be used in the computer program. Methods to generate the block Lanczos vectors are presented in [21-23].

d) It may be more computationally efficient to use the selective reorthogonalization scheme proposed by Simon in [24] and used by Nour-Omid et al in [25,26], than the one presented by Mish in the report under consideration. Also, the one proposed by Leger in [21] yields very accurate results and is not so computationally expensive.

e) As a final comment it is worth pointing out that the proposed Newton-Lanczos algorithm should be a good tool for the 3-D nonlinear analysis of drydock and given the large size of the model, the only one which can make the problem tractable for the computer environment available at the NCEL. However, the programing effort involved in the computer implementation of the proposed Lanczos algorithm within the context of nonlinear analysis and multilevel substructuring is not an easy task.

3.2 CONTACT PROBLEMS

The work reviewed in this section is reported in References [3-4]. This work deals with the construction of algorithms which will handle dynamic contact simulations. Landers in [3] reviews several frictionless, small deformation contact algorithms, and discusses their advantages and disadvantages. The conclusion of the study is that the augmented Lagrangian formulation combines the best features of the other currently available methods, namely, the penalty, the classical Lagrangian and the perturbed

Lagrangian methods. This formulation yields an algorithm that is not as sensitive to the penalty number as the penalty and perturbed Lagrangian methods, and does not increase the number of equations as the classical Lagrangian approach.

In addition the problem of the finite element system of equations being indefinite is also avoided. In the augmented Lagrangian algorithm the Lagrange multiplier is simply added to the right hand side of the equation as a correction term that is calculated through an iteration process. Convergence is assured without requiring that the penalty parameter tend to infinity. Also, the displacements and contact forces are obtained without the need for extra calculations. The work done by Ju el al in [4] is concerned with the development of a perturbed Lagrangian formulation that includes friction forces. The formulation is based on an operator split methodology similar to that used in elasto-plasticity.

Both numerical algorithms have been implemented in the computer program FEAP, and tested through the solution of different sample problems, yielding very good results. Therefore, they seem very suitable for the analysis of the contact problem existing between the walls of the drydock and the adjacent soil.

However, there are at present some serious limitations in the finite element implementation of both techniques. In particular, the contact kinematic assumptions used in [3-4] are only currently valid for 2-D problems, single contact segments and linear interpolation elements. The extension to 3-D cases, multiple contact segments, symmetric boundary conditions and higher order interpolation is still a matter of basic research. Furthermore, the computational cost required to perform the penetration calculations in the 3-D problem might be larger than that required to solve the entire finite element system of equations.

In order to make the problem tractable at the current stage, simpler kinematic assumptions should be made at the time of implementing the proposed algorithms in the computer program for the analysis of the drydock. It is suggested that for the first version of the program, small deformation and linear kinematics based on elementary node-on-node contact or a very simple non-nodal contact should be used. These assumptions were used in less recent work in contact problems, and are reported in [27-28]. These kinematic hypotheses could be improved and updated, within the finite element code, as research in the area of 3-D contact problem progresses.

3.3 COMBINED BOUNDARY ELEMENT AND FINITE ELEMENT METHODS FOR THE SILENT BOUNDARY EFFECT

The work reviewed in this section is reported in Reference [5]. The ultimate objective of this research is to combine the finite element method with the boundary element method in an efficient manner for the solution of large structural-geotechnical problems. It is widely acknowledged that the former permits a detailed modeling of a structural or soil system and provides a suitable computational environment for the solution of dynamic and nonlinear problems. However, as pointed out above, up to this date there are no accurate solutions within the finite element framework to problems involving the modeling of an infinite or semi-infinite media in the time domain. Besides, the polynomial expansions used in the finite element method fail to model singularities (at which all or part of the derivatives are infinite) in an accurate way.

On the other hand, the boundary element method requires only the boundary to be discretized and is based on the Green's function solution for the rest of the domain. This method permits a better analysis of infinite domain and singular problems. Due to the fact that this technique has not been as extensively developed as the finite element method for nonlinear-dynamic problems, it seems that a marriage between both could provide appropriate general solutions to a large number of problems in elastodynamics, and in particular to the soil-structure interaction problem involved in the drydock analysis.

Previous studies at the NCEL have focussed on the coupling between the boundary element and the finite element models, and also on the improvement of the performance of the boundary elements in the near boundary region. The first issue has been addressed by Shugar and Cox in [29], where successful results have been obtained in two-dimensional elastostatic problems with constant stress elements. However, the fact that the resultant stiffness matrix is unsymmetric did not make the method suitable for application in nonlinear soil-structure interaction problems.The reviewed report dedicates attention to procedures that will increase the reliability of the method in the near-boundary region where error is normally excessive, and in this respect the authors devise a recursive element subdivision procedure for both indirect and direct boundary element methods, that yields improved accuracy while maintaining simplicity in the implementation. The proposed adaptive method can also be extended to the combination boundary and finite elements, but this part needs further research.

Unfortunately, techniques to improve the matching between both the finite element and boundary element methods, as well as the finding of general integral solutions for the three-dimensional far field problem in the time domain are still under basic research, and at this stage they can not be applied in the 6.2 Nonlinear Structural Analysis Program. More specifically, further work is needed to produce a stiffness coupling between the boundary element and the finite element methods that, for higher order interpolations, does not violate compatibility along the boundary and that produces symmetric stiffness matrices. The problem of finding a solution to the 3-D far field problem could be somehow connected with the problem of using the boundary element method to develop infinite elements in the time domain.

In order to cope with the problem of the silent boundary effect, it is suggested that finite element techniques in the time domain, reported above, be used in conjuction with the proposed substructuring procedure to account for the energy dissipation at the boundaries of the finite element model.

3.4 BOUNDING SURFACE PLASTICITY MODEL FOR SOILS AND LINEAR ELASTIC FRACTURE MECHANICS FOR CONCRETE

References [6-7] describe the work done under the 6.1 Structural Modeling Program regarding the implementation and validation of the bounding surface plasticity model for cohesive soils. The first work describes the use of numerical algorithms to correct certain computational problems of previous implementations, which already had the capability to model real soil behavior. The computational problems were basically the numerical integration error occurring when using moderate sized integration steps, and the inadequacy of the scaling procedure to return a predicted stress state to the bounding surface when it fell outside.

Robustness has been added, firstly through the use of sub-stepping that allows for convergence even in the case of large size integration steps, and secondly, through a more accurate radial return algorithm to bring a point back to the bounding surface. The improved bounding surface plasticity model is included in the master subroutine CLAY, which can be added to existing finite element codes to supply the incremental material properties needed in the nonlinear analysis. The CLAY subroutine package allows the use of a global iteration scheme, Newton-Raphson or quasi-Newton methods for non-linear iteration. It also contemplates the use of a nearly

incompressible solid model for the soil for those situations in which the soil is saturated in undrained conditions.

The analysis program has been validated as reported in [7] by means of a comparison with a complete centrifuge test of a retaining wall system. The good correlations obtained between the experimental data and the finite element analysis corroborate both the reliability of the plasticity model and the accuracy of the CLAY computer package.

Although the impact that the modifications and the material model evaluation have on the total computational cost for large finite element analysis have not yet been determined, it may be concluded that the technique is ready for implementation in the 6.2 Nonlinear Structural Analysis Program.

Reference [8] describes the work done under the 6.1 Program to find an appropriate fracture mechanics theory for concrete. The author believes, based on his experimental results, that the linear elastic fracture mechanics (LEFM) model is still valid for the modeling of crack formation and propagation in concrete. Although my expertise does not lie in this particular aspect of engineering, I tend to think that this formulation will produce an adequate and simple model for the cracking and fracture of concrete and suggest its implementation in the 6.2 Nonlinear Structural Analysis Program.

4. Conclusions

A review has been made of the algorithms developed under the 6.1 Structural Modeling Program to evaluate their applicability to the objectives of the 6.2 Nonlinear Structural Analysis Program. The major conclusions may be summarized as follows:

The proposed reduced coordinate algorithms should have a solid application for the problem at hand. However, it is recommended that the "block Lanczos" method be used to generate the approximating subspace of Lanczos vectors. These should be obtained taking into consideration the spatial distribution of the 3 dimensional earthquake components. It is also proposed that this technique be used in the context of multi-level substructuring. Serious consideration should be given to the fact that the programing effort involved in the computer implementation of the proposed Lanczos

algorithm within the context of nonlinear analysis and multilevel substructuring is considerable.

The algorithms made available to solve the nonlinear contact problem are applicable to the 6.2 Program. However, it is necessary that simpler contact kinematic assumptions be made for the 3 dimensional finite element implementation of these algorithms. These kinematic hypotheses could be improved and updated, within the finite element code, to more complicated schemes as research in the area of the 3-D contact problem progresses.

The combination of the boundary element and the finite element method seems to be one of the most promising approaches for the solution of the silent boundary effect in the time domain. Although serious consideration is being given to it in current research, no general algorithm within the context of 3 dimensional elasto-dynamics is ready as yet. It is therefore proposed that finite element techniques in the time domain, reported in the literature, be used in conjunction with the substructuring procedure mentioned above to account for the energy dissipation at the boundaries of the finite element model.

The improved bounding surface plasticity model, implemented in the computer package CLAY, and validated through experimental testing, should be of direct application to model the nonlinear conditions of the soil near the walls of the drydock. The linear elastic fracture mechanics (LEFM) model seems to be valid for the modeling of crack formation and propagation in concrete.

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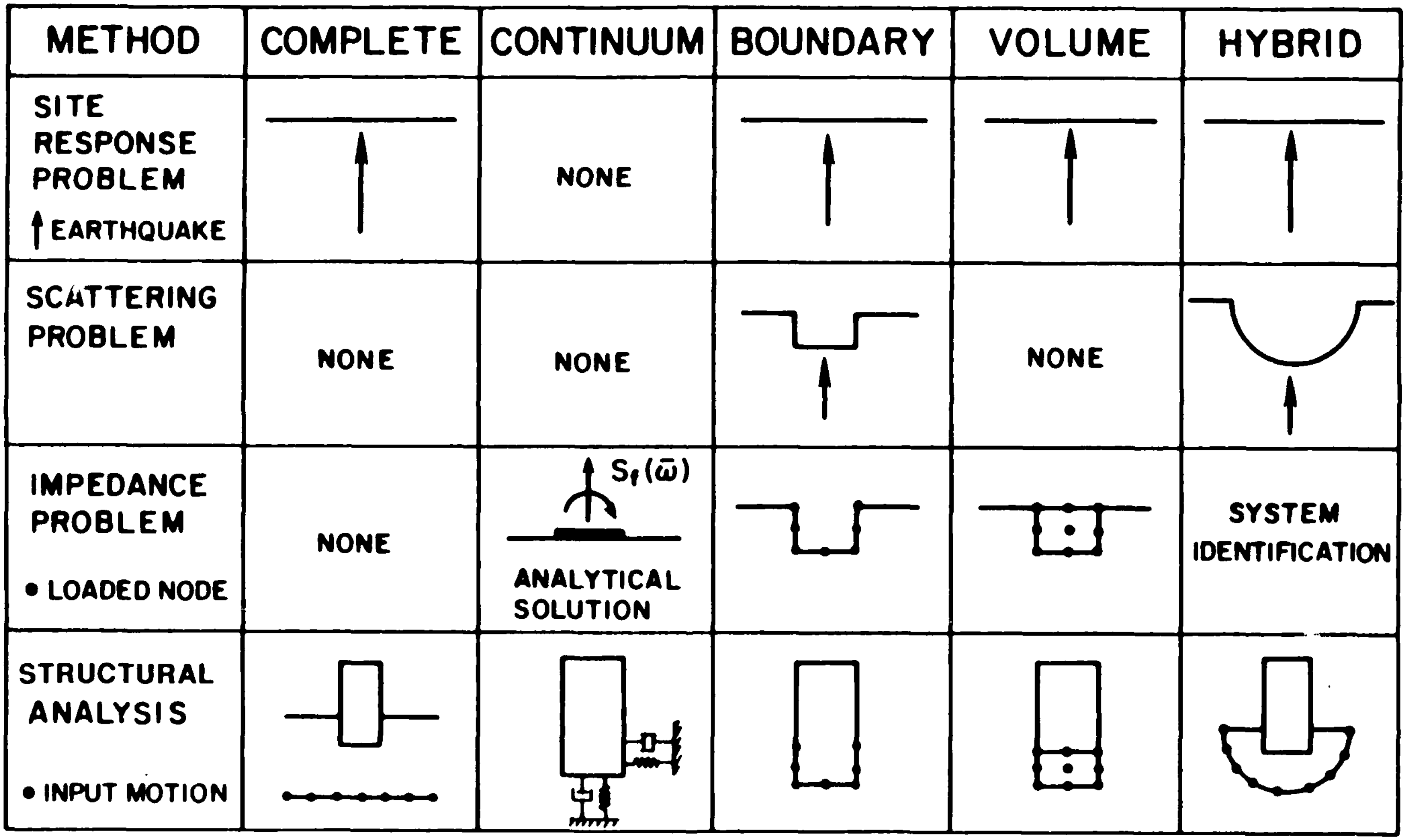

Fig 1 .- Summary of the frequency domain methods.

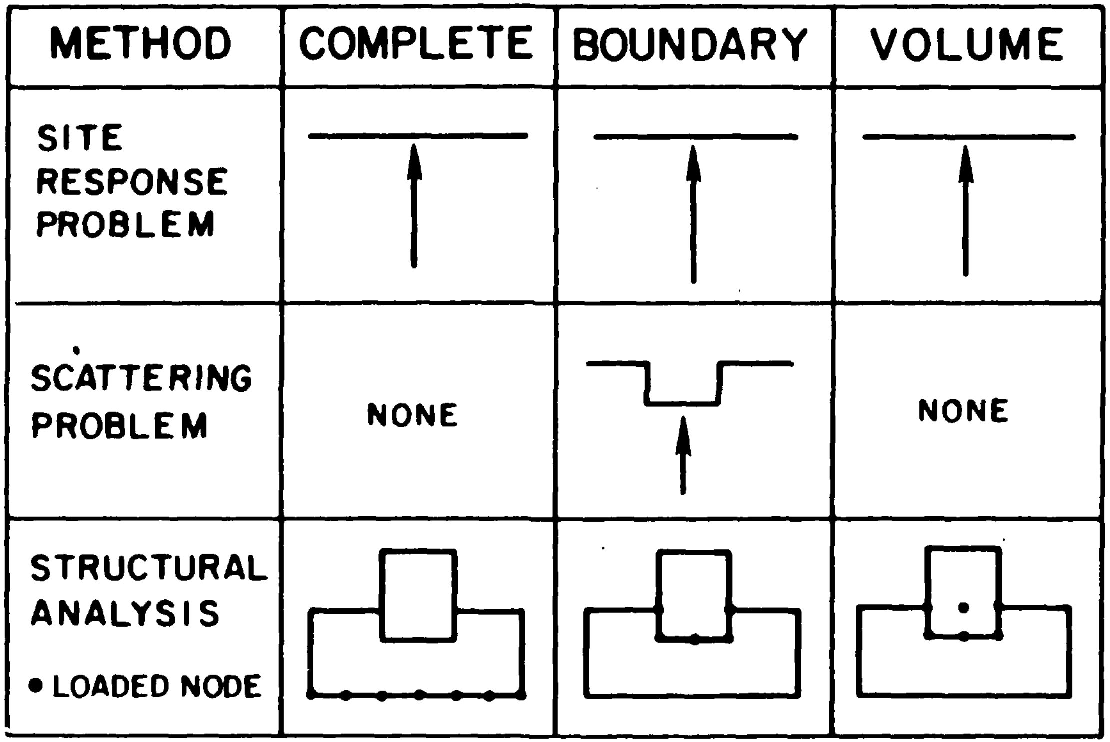

Fig 2 .- Summary of the time domain methods.

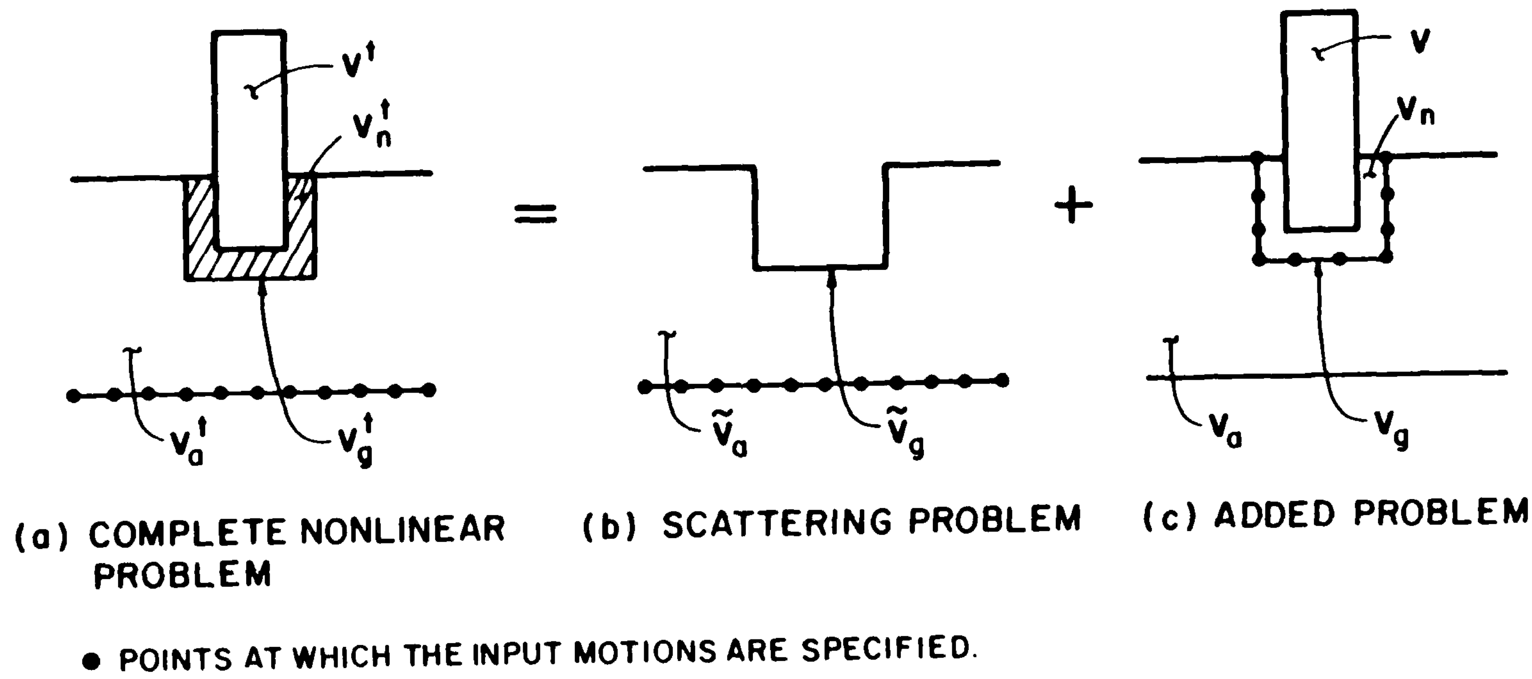

Fig 3 .- Two step solution for the nonlinear problem.

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